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WAVE POWER

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SUMMARY

An analysis of wave data from the NE Atlantic shows that the average power density along the UK west coast is about 80 kW m^{-1} or 120 GW overall, more than twice the installed capacity of the CEGB. The power supply is also extremely variable, for 1% of the year in excess of 1 MW m^{-1} and for a further 1% very close to zero. This variability not only creates severe technical problems in any attempt to harness wave power, but the lack of firmness means that the value of any power brought to shore is limited to the value of other forms of energy which can be so conserved. This value depends on many factors including fuel cost escalations and the load factor of the wave power supply, but initial estimates indicate that it could be of the same order as the cost of installing a wave power system.

In addition to describing some of the promising devices which could be used for extracting wave power, the problems associated with designing a conversion and transmission system to link the variable supply of energy at the device into a system, meeting the more even requirements of the consumer are discussed. It is shown that it may be possible to tailor the device and conversion plant characteristics to achieve this power regulation without the need for excessive overload ratings and large quantities of storage.

The importance of obtaining a proper understanding of the 'seakeeping' characteristics of devices at sea in a wide range of operating conditions and with realistic power take off systems is emphasised and questions of survival, reliability, maintenance and plant life and the environmental impacts of wave power are also considered.

Very rough estimates of the cost of wave power systems suggest that a capital cost of £400 to £800 per kW is possible and it is concluded that if satisfactory solutions can be found to the many remaining technical and engineering problems without an undue increase in this cost, there is a possibility that wave power could make a valuable contribution to Britain's energy needs.

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1. INTRODUCTION

During 1974 the Research Department of the CEGB undertook a wide ranging 'Long Term Study' of development options open to the Board over the next 20 to 30 years. In the course of this study each of the renewable energy sources was examined for its relevance to the energy situation in Britain and in particular for its relevance to the CEGB's requirements as an electricity utility. Whilst none emerged from this analysis as directly competitive with nuclear power, one or two were selected as worthy of closer study. Wave power, despite being the least extensively researched of all the options, appeared to be particularly attractive, primarily because of the large amount of energy potentially available from around the British coasts. Furthermore, it was apparent that the risks involved in a development programme could be limited, since small scale prototypes could be tried out individually at sea and the essentially modular nature of wave power would not necessitate the sort of massive investment in a single project as required, for example, for tidal power.

At the same time, the inventors were busily demonstrating new ideas in advanced wave power machines and producing some remarkable performances. In particular, Mr. S.H. Salter of Edinburgh University, had evolved a 'nodding duck' shape, Figure 1, which in tank tests with regular waves had extracted 90% of the incident power, (Salter, 1974), and a system devised by Sir Christopher Cockerell consisting of a series of coupled rafts designed to contour to the wave profile, Figure 2, had given efficiencies of around 50% in tests carried out by the British Hovercraft Corporation for a company, Wave Power Ltd., (Wooley and Platts, 1975). Other promising concepts included a development, Figure 3, of the air bell system from Y. Masuda in Japan, which was already in use in many parts of the world generating power for self-powered navigation buoys, (Masuda, et al., 1974).

As a consequence of these preliminary studies a small research programme on wave power was initiated in 1974 at the CEGB's Marchwood Engineering Laboratories near Southampton. The aims of this programme are to study the characteristics of the available energy, examine methods of harnessing it and identify the main problems which will need to be overcome before wave power can be exploited on a large scale in order that the cost and the feasibility of integrating wave power into the CEGB generating system can be reliably assessed.

In this Note each of these areas will be discussed in turn, highlighting the problems which have been identified.

2. THE CHARACTERISTICS OF THE AVAILABLE POWER

2.1 Simple Wave Theory

Linear wave theory, (Milne-Thompson, 1962), is an excellent basis for understanding some of the main characteristics of wave power.

A simple progressive sinusoidal wave of amplitude, a, wave length λ, and period T, travelling in deep water (by which it is meant that the depth is greater than half a wavelength) has a surface profile

$$y = a \sin (kx - \omega t)$$

in which $k(= 2\pi/\lambda)$ is the wavenumber and $\omega(= 2\pi/T)$ is the angular frequency.

A fluid particle in the surface moves in a circular orbit of amplitude, a, and a velocity amplitude of $a\omega$, and fluid particles below the surface also move in circular orbits of decreasing amplitude, as $a\exp(-ky)$, where y is the depth. The total energy, E, per unit of surface area contained in the circular fluid motions (kinetic) and in the variation in potential energy above and below the mean water level is

$$E = \tfrac{1}{2}\,\rho g a^2 \qquad (1)$$

where ρ is the density of sea water and g the acceleration due to gravity.

The speed with which the wave propagates, the phase velocity c, can be written variously as

$$c = \lambda/T = \sqrt{(g/k)} = gT/2\pi \qquad (2)$$

and the speed with which the energy propagates, the group velocity v, is one half of this.

The power associated with a monochromatic wave is therefore

$$P = Ev = \rho g^2 a^2 T/8\pi \qquad (3)$$

per unit width of wave front.

It will also be seen from the forms of equation (2) that the wavelength and period are simply related as $\lambda = gT^2/2\pi$, a 7 s wave having a wavelength of 75 m, a 10 s wave gives 150 m and so on.

2.2 Waves in the Ocean

Ocean waves are, of course, generated by the wind so wave power is in fact another form of wind, and therefore solar, power but with an important difference. Water waves transfer energy at an extremely high efficiency and with attenuation distances of the order of several thousand kilometres (it is said that in the absence of wind the amplitude of a wave halves in as many miles as the wavelength is measured in feet), and as a result the waves arriving at one point may have originated in a storm a very great distance away. The ocean therefore acts as a very large collecting area and even when waves are not being generated by a local wind (the wind sea), there is a good chance of waves from remote wind fields (the swell sea), being present.

2.2.1. The wind sea

The waves in a wind generated sea are far from the idealised monochromes of section 2.1, but can be treated as the linear sum of many such monochromatic waves of random relative phase distributed both in direction, θ, and across the frequency spectrum, f. It is common practice to assume that the principle direction, θ_o, is the wind direction and the energy spectrum is represented as the product of a one dimensional spectral density function $\varepsilon(f)$ and a spreading function $g(\theta)$. In this way the directional properties are detached from energy and power estimation although they are still significant in relation to wave power systems.

The most common way in which oceanographic data have been presented are in terms of a 'significant wave height', H_s and 'zero crossing period', T_z, (Tucker, 1963) and the preferred form of $\varepsilon(f)$ is that of Pierson and Moskowitz, (1964)

$$\varepsilon(f) = Af^{-5}\exp(-Bf^{-4}) \qquad (4)$$

where A and B are constants related to windspeed and fetch or H_s together with one of the representative wave periods.

In terms of H_s and T_z, the constants A and B in (4) become

$$\left.\begin{aligned} A &= H_s^{\,2}/(4\pi T_z^{\,4}) \\ \text{and}\qquad B &= (1/\pi T_z^{\,4}) \end{aligned}\right\} \qquad (5)$$

and the power of the wave, P, is

$$P \simeq .55\, H_s^{\,2} T_z \text{ kW m}^{-1} \qquad (6)$$

where H_s is measured in metres and T_z in seconds.

From a knowledge of H_s and T_z therefore it is now possible to estimate the available power and obtain information on the distribution of energy across the frequency spectrum for a given wind sea. By considering all combinations of H_s and T_z in a given sea area, it is then possible to build up a picture of the type of performance characteristics which an ideal wave power system should have.

2.2.2. The swell sea

From the form of the phase velocity $c = gT/2\pi$, equation (2), it is apparent that away from a storm or generating site the wind sea will spread itself out with the longer, low frequency, waves travelling away from the centre more quickly than the shorter, high frequency, waves. At great distances from the generating site, the high frequency waves will have been significantly attenuated but almost plane long wavelength monochromatic swell waves of slowly increasing frequency will be detected, (Barber and Ursell, 1948). The power associated with these waves will be almost exactly that predicted from the simple theory, equation (3). Swell waves can occur in isolation, in combination from a number of sources or more commonly with a wind sea superimposed upon them.

2.3 North Atlantic Data

The Institute of Oceanographic Sciences and other organisations, collect data from wave buoys, weather ships, light ships and straightforward sightings from ships in passage. A particularly comprehensive set of published data for the North Atlantic comes from the weather ship site 'India' (50°N 19°W), (Draper and Squire, 1967). The 'scatter diagram' of the frequency of occurrences of H_s and T_z combinations in parts per thousand for India is reproduced in Figure 4.

By using equation (6) to estimate the power associated with each of the combinations in Figure 4, it is easily shown that power levels of 30 to 40 kW m^{-1} are amongst the most frequent and the average over all conditions is about 80 kW m^{-1}. This confirms the power base used in the recent studies of wave power by Salter (Salter, 1974) and (Denton, et al., 1975) and when one considers that there are at least 1500 km of Atlantic facing coastline in the United Kingdom, the total power which is potentially available amounts to 120 GW on average which is more than double the present installed capacity of the CEGB.

The distribution of energy across the frequency spectrum is shown in Figure 5 for typical 'India' sea states based on equations (4) and (5). It is clear from each example that although the wave system has been characterised by a single period the energy is distributed across a full 2:1 frequency band. For example, the H_s = 10 m, T_z = 13 s wave system whose characteristic frequency is $1/T_Z$ = .077 Hz, has its energy distributed in waves of .04 Hz to more than .09 Hz (25 s down to 11 s in terms of period).

2.3.1. Variability in the supply

In addition to giving an overall feel for the scale of wave power, the scatter diagram also provides the first indication of the extreme variability of the wave energy supply, for something more than 1% of the time wave heights in excess of 10 m and periods greater than 11 s are experienced corresponding to average power levels of 1 MW m^{-1} and more. At the other end of the scale there are significant periods, again about 1% of the time, when there are hardly any waves at all resulting in an absence of power. These will occur at random, which means that wave power cannot be regarded as "firm power" and its value will have to be assessed for its ability to conserve other forms of prime energy and reduce running costs on conventional plant and not as an alternative to nuclear or conventional fossil fuelled power stations.

A useful way of presenting this variability is in the form of a 'supply load factor', the energy actually available over a given period up to a specified power level divided by the energy which would be produced if the specified power output could be maintained throughout that period. Figure 6 shows the data from Figure 4 presented in this way, highlighting an attractive feature of wave power, a seasonal variation in the energy supply more in winter than in the summer, which compares favourably with the pattern of electricity demand in the UK. Only very limited, and probably rather unrepresentative, data existed for the month of February and this has not been included on Figure 6.

The data collected at 'India' (Draper and Squire, 1967) amounts to about one year of records taken at three hourly intervals in a total period of about ten years and is therefore rather sparse. A detailed plot of each record nevertheless produces more interesting information. The plots for 'January' for example, Figure 7, show large differences from one year to another, half of the data collected in 1963 giving power levels of less than 50 kW m^{-1} whereas that for 1962 is only occasionally below 150 kW m^{-1} and often exceeds 500 kW m^{-1}. Surprisingly rapid changes in power levels are also highlighted, sometimes as much as 200 kW m^{-1} in one 3 h interval.

This extreme variability in power level extends even to the minute by minute timescale. Longuet-Higgins (1956) observed that for narrow spectra the wave amplitude, a, is distributed according to the Rayleigh distribution. From this an exceedance curve, the proportion of time that the instantaneous power exceeds a given level for a stationary sea state can be deduced, and it is found that power levels of ten or more times the mean will occur for about 1% of the time. This has been confirmed from spot checks of wave records made by IOS at Station India where, for example, in one 20 minute record taken during a force 8 gale the mean power was of the order of 750 kW m^{-1} with peaks greater than 7.5 MW m^{-1}. For a continuous period of more than one minute, about three wave cycles, the power level exceeded 3 MW m^{-1} equivalent to the whole output of the CEGB from only 15 km of wave front.

One final piece of information which can be deduced from the scatter diagram, Figure 4, is that there is a reasonable correlation between the significant wave height and the wavelength,as indicated by the lines of constant wave slopes (H_s/λ) of 1:20 and 1:40 included on the diagram. From this it will be recognised that the extremely high wave powers will tend to be associated with very long wavelengths a factor which can be significant in the design of a practical, secure, wave power system.

2.3.2. Directional characteristics

The data collected at 'India' and, with very few exceptions, elsewhere, are point data, which only give a measure of wave elevation but do not include directional information. As indicated in 2.2.1 the mean direction of the wind sea is taken to be the wind direction. It is common knowledge that the prevailing wind in the North Atlantic is westerly and the data published by the National Physical Laboratory (Hogben and Lumb, 1967) confirms that 45% of wind seas approach from the westerly quadrant in the sea area containing station India. A further 24% comes from the southerly quadrant, 19% from the north and the remaining 12% from the east. What has not yet been determined is how the energy supply is distributed among these directions, nor therefore, since India is well out into the Atlantic, how much of the energy assumed to be available will in fact be present at likely wave power generating sites closer to the coast, say within 20 km, where there is a good deal of shelter from the east and often the north and south too.

The direction of the swell sea if it is present, is not a function of the local wind, but of the location of the swell source and geographical factors.

The form of the spreading function $g(\theta)$, which is a measure of the directional distribution of the incident wave energy about the mean direction, is usually taken to be $\cos^{2s}(\theta-\theta_0)$. The exponent 2s is commonly taken as 2 but at low frequencies, and especially for residual swells, values of s of 10 and even 20 have been recommended under which circumstances the waves are to all intents and purposes plane. This introduces another concept of interest to the wave power system designer, crest length. The sea is not many progressive waves one behind the other with their crests even and parallel, except close in shore or when only swell exists, but a peaky pointed surface with a characteristic crest length. According to the values of s in $g(\theta)$, the average crest length can be anything from 1.7 to 3 times the wavelength.

3. WAVE POWER - THE PROBLEM

Before proceeding to a more detailed discussion of possible systems for extracting wave energy, converting it to a useful form and transmitting it to shore, it is now worth considering what basic characteristics such a system should have in the light of the known characteristics of the energy supply.

It is apparent that on average the availability of wave power is sufficiently large that it is a potentially valuable resource, for the United Kingdom at any rate, particularly in view of the seasonal peak which occurs in the winter and closely matches the UK demand pattern for electrical power. Since it is unlikely that any wave power system can actually be 'cheap' to build, a satisfactory return on capital will most probably require operation at a fairly high load factor, particularly in the winter when the opportunities for saving expensive fossil fuels are greatest. On the basis of Figure 6, this would imply designing for the 50 to 150 kW m^{-1} power but, in order that this curve can be interpreted as a load factor curve, this actually means that the system shall continue to operate at or near the selected design level even when much more severe conditions prevail.

What is required then is a system which will accept a random energy input of extreme variability and produce a smooth output within a much narrower power band. Ideally the system would include an array of devices with a wide enough acceptance angle to cope with the directional spread of incident energy which can also cope with as wide a range of principal incident directions as possible. The array would be connected into a conversion and transmission system which would provide sufficient short term smoothing to overcome at least minute by minute and if possible hour by hour variations in delivered power. Finally, it may be advantageous if the whole assembly has a performance characteristic which helps to minimise the variation in output by, perhaps, being very efficient in low power level seas, which have a small wave height and generally in consequence, period, and become progressively less efficient as both period and height increase. If, for example, a system could be 100% efficient at 100 kW m^{-1}, 50% at 200 kW m^{-1} and 5% at 2000 kW m^{-1} an output of about 100 kW m^{-1} could be achieved for up to 45% of the time in winter and up to 33% taking the year as a whole (averaged over a number of years) and if moreover a high efficiency could be maintained at lower power levels valuable injections of up to 100 kW m^{-1} could be available for much of the remainder giving an annual load factor of up to 50%.

The problem then is to identify a system with these general characteristics which can be built to survive the hostile extremes of the ocean environment with good reliability and long life at a cost, including the environmental, operational and other problems associated with constructing and incorporating wave power on the electricity system, which can be justified in terms of the capitalised value of the energy savings it would make possible.

4. WAVE POWER DEVICES

Up to the present time most of those who have interested themselves in wave power have concentrated their efforts on the device which is put to sea to couple to the incident wave system. As a result many patents exist for ramps, floats, flaps, systems involving fixed and moving air bells and 'wavepumps' of various descriptions. With certain notable exceptions, which will be discussed later, most of these patents presume a passive device coupling to either the 'potential' or 'kinetic' energy components, i.e. the surface displacement or the circular fluid particle motions and the general level of physical understanding has not been particularly high.

4.1 Ramps

Strictly speaking only ramp and similar schemes can be regarded as passive. The underlying operating principle is that as deep ocean waves travel into shallowing water they progressively steepen and the wave energy is converted into forward momentum, most of the energy in a wavelength being concentrated in the kinetic and potential energy of the crest. The forward momentum of the fluid is converted into an hydraulic head on a sloping sea wall, water being carried over the top to charge a 'high' level reservoir, from which power can be produced by returning the water to the sea through a load head turbine working on the difference between the reservoir and the mean water levels. The only moving parts are the turbines and the only variables are the slope and height of the ramp. Such a scheme was proposed for Mauritius (Bott, 1975), taking advantage of the small tidal range and a particular coastal structure but for the British Isles, where the tidal range is large compared with likely ramp heights, ramp schemes do not seem to be attractive despite their undoubted simplicity and reliability and substantial inbuilt storage capacity. Another factor which confirms this view is that the performance characteristics of such schemes are not in line with the requirements set out in Section 3. In a limited assessment of such schemes using overtopping data given in Wiegel, (1964) for a run up slope of 1:3 and a range of ramp heights above still water level it was found that not only was the peak conversion efficiency only about 25% (measured as the rate of transfer of potential energy over the ramp relative to the power of the original deep water wave) but, more significantly, the performance was worst at small wave heights.

4.2 Floats

The visible part of a wave system is of course the surface motion and not surprisingly there have been many schemes for allowing floats to heave in response to this motion taking power out at a pump or similar device attached to a mooring line. The problem with such schemes is that either the link to the sea bed becomes very complicated and expensive or the float does not restrict itself to the heave motion from which energy is to be extracted but it pitches and surges as well with an attendant loss of performance. One interesting exception is the so called resonant point absorber, (Budar and Falnes, 1975), which can, in principle, extract energy at a high efficiency from a wave front of width $(\lambda/2\pi)$ regardless of its own size. Evans (1976) has confirmed this result but notes that for very small devices, very large amplitudes of motion are required.

4.3 Flaps

In deep water, the horizontal component of the motion of the fluid, which decays as $\exp(-ky)$ with increasing depth, can be closely matched to an oscillating flap hinged at something like $.4\lambda$ below the surface. In between the completely undamped motion, when the flap moves freely with the incident wave and generates a new wave with the same energy to the rear, and the overdamped condition, where the flap barely moves and the incident wave is reflected, there is an optimum damping when almost half the energy can be extracted, the remainder being contained in reflected and transmitted waves of reduced size. Systems of this type also require complicated and expensive sea bed connections.

4.4 Air Bells and Wave Pumps

Early ideas for these devices were also based on the motion of the fluid surface. It was conceived that if an air bell was supported with its open bottom a little way below the water surface, passing waves would cause a cyclic pressure variation in the trapped air and, therefore, if the vessel were connected through a rectifying valve arrangement to a small turbine,power could be produced. This is the operating principle of the 300 or so self-powered navigation buoys, designed by Masuda in Japan, in use around the world.

Wave pumps also work off subsurface pressure variations by pumping fluid round a circuit containing a hydraulic motor using a succession of suitably spaced collapsible cylinders connected through non return valves. A common error made in designing such systems is to assume that the pressure at all depths is the hydrostatic head $\rho g(y + \xi)$ where y is the depth and ξ the instantaneous wave height. In fact the pressure amplitude decays at the same rate as the velocity amplitude and neither system will function if deeply immersed.

4.5 Promising Device Concepts

Although the general device types described above seem to be unpromising, it is in fact variations on these early themes which are among the leading contenders for highly efficient and hopefully practical devices.

The Cockerell pontoons, Figure 2, can be regarded as a series of floats which progressively extract the energy of a wave as it progresses down the line. The ingeneous aspect of this invention is that by hinging the floats together and extracting power from the relative motion of adjacent elements, the need for complex sea bed couplings is minimised to the mooring, power and control system connections.

The Salter duck can be similarly regarded as a backless flap. A freely moving flapping plate transmits all the incoming energy and can be regarded as having absorbed all the energy at one face and re-radiated it from the back. The Salter duck overcomes this by the very carefully designed shape, Figure 1, which is chosen such that when the duck oscillates in roll about the correct centre, the front of the duck, which faces the waves, moves almost exactly with the fluid motions absorbing all the energy. The rear section, which is circular, does not displace any fluid and cannot therefore generate a transmitted wave. In two dimensional tank tests using plane monochromatic waves, Salter has extracted about 90% of the incident energy.

Working on the principle (as Cockerell) of progressively extracting energy from a number of relatively inefficient units, Masuda has proposed and tested a number of configurations of multi-chamber air buoys.

It is now necessary to consider how these devices might perform in a variety of sea conditions to gain some idea of the structural size which would be needed at full scale and the extent to which their performance characteristics are likely to conform to the general requirements set out in Section 3.

The most published information which is available relates to the Salter device. In late 1974, the CEGB conducted tests in Edinburgh with one of Salter's own early models, a device 10 cm in diameter and 30 cm wide and damped by an electronically controlled load. These tests also gave a peak extraction efficiency of about 90% but showed a fairly rapid fall off at frequencies on either side, Figure 8, Curve B. The position of the peak and the general shape of the response curve for this model fitted well with a simple theoretical analysis of the device behaviour, (Count and Glendenning, 1976), Figure 8, Curve A, the differences being readily explained when the operating phase between the duck and wave motions was taken into account. Despite the relatively narrow bandwidth the device had a very respectable performance over the band needed to match efficiently to real sea spectra as defined by equation (4). Scaled to the Atlantic, however, this duck would need to be about 40 m in diameter but, since it is effectively part of a damped spring-mass system, this could clearly be reduced by increasing the system inertia. This idea was tested by the CEGB in May 1975 in the NPL wave tank at Hythe, using two, much larger, ducks (2.4 m long and 0.5 m wide) mounted in a back-to-back configuration, one duck acting as the load for the other. The results obtained, in order of increasing inertia, are shown on Figure 8, Curves C, D and E, and it can be seen that both the increase in the peak operating period and the reduction in efficiency are very much as predicted. Scaled to the North Atlantic Curves C, D and E correspond to ducks of 18 m, 14 m and 9 m respectively.

The duck, being asymmetric, needs a minimum of ballast in the 'nose' to hold it down in a level attitude. The performance of a device with an inertia corresponding to this minimum ballast is shown in Figure 8, Curve C. Combining this with a range of energy spectra as defined by equation (4) over a range T_z indicates, Figure 9, that an 18 m diameter duck would have a performance in the sea peaking at about 45% efficiency (for plane waves) and maintain a good performance over the range of T_z from 7 s to 10 s before falling away at the higher values of T_z which are associated with the very high power levels. In his experiments at Edinburgh with a more deeply immersed duck, Salter has obtained even higher efficiencies with broader bandwidths, Figure 8, Curve F, which would produce peak 'sea' efficiencies of around 67% and more recently still he has published (Salter, et al. 1976), results for a duck with a sophisticated control unit which includes reactive loading components from which efficiencies of over 80% over a full 2:1 bandwidth were obtained. This would imply possible sea performances peaking at about 80%

whilst still showing a fall off in performance at the higher power levels. With this system, Salter quotes duck diameters of 10 m to 15 m for the North Atlantic.

Recent tank tests carried out by the CEGB on the Cockerell raft system indicate that it is possible to achieve broadly similar performance characteristics with that device. Though the pontoon system has a greater overall length, its shallow draught may mean that when sized for the North Atlantic, it will require no more structural material than the duck. The only results which are currently available from Masuda suggest that this too displays the same overall characteristics.

One characteristic which is not taken into account by these performance considerations if the ability of the device to accept energy from a number of directions should the selected site demand such a capability. If, ultimately, one recognises that a very long line of devices will be required to produce significant quantities of power, i.e. Gigawatts, then a side-to-side absorption capability is not required although the Masuda design being genuinely omni-directional could function in this way. The Masuda can therefore also absorb energy from the rear as well as the front and if so designed so too could the contouring raft. Only the Salter design, being deliberately asymmetric would not be able to extract energy from the rear. All of the devices can be expected to cope with a fairly wide range of incident directions, and directional spreads, of the wave energy so long as the width of each element is kept well below a wavelength.

A further factor not so far taken into account is the effect on performance which a realistic mooring and loading system might have and this is discussed in the next section under the heading 'Seakeeping'.

5. OVERALL SYSTEM CONSIDERATIONS

The device for extracting the energy, although very important, is only the first link in a long chain of equipment needed to convert the wave energy into a useable form, transmit it to shore and feed it into either the electricity supply system, or possibly, that of some other energy consumer or distributor. If a single key area can be identified in the study of wave power it is probably the design and engineering of an economic and efficient conversion and transmission system connecting the device to the consumer. It is already clear that this system will have to accept a random and extremely wide ranging energy input but it is only now that the wave and device characteristics are better understood that a meaningful study of the options can be contemplated. Other questions such as seakeeping, survival in storm conditions, reliability, maintenance and plant life considerations and operational problems, which may arise in the existing CEGB network as a result of incorporating wave power, will all have to be answered before a reliable assessment of the technical and economic suitability of wave power as an alternative energy resource can be made.

5.1 Conversion and Transmission Systems

A simplified block diagram showing the probable component combinations which will make up a complete wave power system is shown in Figure 10. Many detailed, but purely speculative, conversion systems can be conceived within the framework of this diagram but here only some of the more obvious routes and problems will be described.

Each device must work against a load of the correct characteristics. So far most experimental results have been achieved with linear (velocity proportional) damping, the effects of non linear loading systems, which might well arise in practice, have not yet been assessed.

The initial motions are the slow oscillation (at typically .1 Hz) of one surface relative to another. Except in the case of the Masuda system in which displaced air and air turbines are an integral part of the design, a mechanical linkage will be required between the moving structure and the load. Possible linkages include levers or gears, which could be incorporated into bearings, or even chains. The very low initial velocities mean that very large torques are involved in transmitting powers which are modest by power engineering standards. For example, if a device produces 1 MW whilst oscillating with an amplitude of 15^{o} at 0.1 Hz, the torque amplitude at the device is about 1200 tonne m which is nearly eight times the torque on the shaft of a 500 MW power station alternator. In general it will not be possible to consider linkages which will convert the oscillations into unidirectional rotation since the amplitudes of oscillation will be varying from wave to wave even in a stationary sea.

The load in each device can be electrical, hydraulic or pneumatic. In the case of the Masuda it need rotate in only one direction, but in the other devices a reciprocating motion albeit possibly many turns in each direction, must be considered. The primary load will be subjected to the full randomness of the wave system and it must be rated for a much higher instantaneous power level than the design average output level. The characteristics of the load and its associated control circuitry will be significant here.

Consider a load with a maximum average power rating P_p. If the load can be controlled to continue to give an output of P_p even when the input power exceeds this level, for example, if the damping is reduced to compensate for excessive velocities, then using the Rayleigh distribution of wave amplitude, the relationship of output to $P_p/\bar{P}$, where $\bar{P}$ is the time averaged input power, would be as in Figure 11, Curve A. When the input power equals the rated power, only just over 40% of $\bar{P}$ is available as output, by $P_p/\bar{P} = 3$, the conversion efficiency has reached 78% and the improvement continues slowly for larger values. Systems which 'fail safe' and produce no output when the design level is exceeded will produce a much smaller output at a given overload rating, Figure 11, Curve B.

This characteristic would be at first sight give rise to a need for all the items of plant which receive an unsmoothed input to be very highly rated and, in consequence, be operated at an uneconomically low load factor. Interestingly however this may not be the case. If, for example, one considers the particular device performance, Figure 9, in combination with the overload characteristics, Figure 11, over a range of sea states as shown in Table 1, then after the device efficiency has been taken into account the wave power range of 35 to 1090 kW m^{-1} has been reduced to 15 to 174 kW m^{-1}. If in addition the conversion plant has a peak rating, say, of 100 kW m^{-1} the variable overload rating has the effect of reducing the range still further, the output of the lower power levels being unaffected because of the relatively large margin, but the higher levels being reduced by one half and two thirds respectively. Of course the overall characteristics of each device with its associated system will have to be examined very carefully before the full implications of this power levelling effect can be established.

TABLE 1

Wave Height H_s Crossing Period T_z	m s	3 7	5 9	8 12	12 14
Wave Power P	kW m^{-1}	35	130	420	1090
Transferred Power, P, (P_1 = P x device efficiency using Figure 9)	kW m^{-1}	15	43	84	174
Output Power P_o (P_o = P_1 x overload factor using Figure 11 and P_p = 100 kW m^{-1})	kW m^{-1}	14	30	38	52

Whatever device is finally selected, it is probable that the output from a large number of small units will be combined to provide a relatively smooth output of a size suitable for the type of transmission system chosen. If this is electrical with the final aim to connect into the CEGB grid, then a reasonably sized assembly might be about 1000 MW. If the maximum average output power that the plant is designed for is, say, 50 to 100 kW m^{-1}, then such a 1000 MW installation would be between 10 and 20 km long, made up from assemblies 300 m to 1000 m long in the case of the Salter system, or from many narrower pontoon strings or individual buoys in the case of the others.

The random output from each independent primary load will have to be combined either at one central point or at several sublevels. The earlier this combination of outputs, with attendant smoothing, can take place, the lower the rating of the main transmission components needs to be, since they would no longer have to cope with peaks.

In addition to the Masuda air turbine, the following systems can be contemplated :-

(i) Direct electrical loading

In view of the low initial velocities in the system, it will be necessary to use highly geared reciprocating alternators. The variable frequency output so produced could be rectified and smoothed either with local storage capacity, using batteries say, or for preference by somehow combining the outputs from a large number of devices and smoothing the residual ripple. A further alternative, which may be especially attractive, is to produce hydrogen electrolytically from the random DC output and use that as the energy storage and transmission medium; the floating factory concept.

There are clearly many difficult problems with this approach, the reciprocating alternators and rectifiers having to operate over a range of output power and frequency which is well outside normal practice, and with many small generating units involved, perhaps no more than 1 MW or so each, overall control will be very complicated.

(ii) Hydraulic loading

It is more common to think in terms of hydraulic (water, including sea water, or oil) systems to load wave power devices. A major advantage of hydraulic systems, for the electrical engineer, is that an accumulator system can be installed before any secondary convertor, such as a turbo-alternator set, so allowing steady generation but even the provision of storage for several minutes' worth of the full rated output may prove difficult to accommodate on board the device. There will also be additional costs and losses resulting from the introduction of another stage in the conversion and transmission process.

Common to all systems will be the need to provide low and high power transmission links from the independent floating devices either to the shore or to a fixed off shore platform functioning as a control centre cum sub-station and main transmission head. On the assumption that the devices are to be sited well off shore the latter is the more likely and it would then be reasonable to expect the preferred transmission link to be a HV DC cable. On shore a sub-station/inverting station with transmission links connecting to the existing electrical grid will have to be provided but this is established technology.

5.2 Performance of an Integrated Wave Power System

Up to now it has been convenient to consider the sea, the devices and the conversion and transmission system as separate, albeit linked, elements of the total system. It must however be remembered that they in fact make up a dynamic whole and just as the behaviour of the flapping plate, Section 4.3, is radically altered by changes in the applied damping, so too will the performance of any other wave power device. The extent to which the characteristics of all parts of the system must simultaneously be taken into account is perhaps best illustrated by noting that the pressure forces which the waves exert on the body, which have to be known before its motion and performance can be determined, are themselves functions of that motion as well as the body shape and the incident wave field.

5.2.1. Seakeeping

The study of the dynamic response of floating structures, usually ships, is commonly referred to as seakeeping. A ship can move with six degrees of freedom, three translation modes (heave, sway and surge) and three rotational modes (pitch, roll and yaw). The equation of motion in each of these degrees of freedom, with a co-ordinate ϕ, takes the usual form

$$I \ddot{\phi} + B \phi = f e^{i\omega t}$$

where I and B are respectively the body inertia and the spring constant due to buoyancy and f is the forcing term, which may be complex, which is the resultant of the hydrodynamic pressure forces acting on the body. Theoretical seakeeping shows that it is possible to evaluate f as three separate components

$$f = F_o - I'(\omega) \ddot{\phi} - K'(\omega) \dot{\phi}$$

in which F_o is the resultant of the exciting force in the ϕ direction which the incoming wave would exert on the fixed body, and $I'(\omega)$ and $K'(\omega)$ are the ϕ components of the forces acting on the body, when it is forced to move in still water, in phase with acceleration and velocity respectively. These are commonly referred to as 'added mass' and 'added damping' respectively and are incorporated in the equation of motion as

$$(I + I'(\omega)) \ddot{\phi} + K'(\omega) \phi + B \phi = F_o e^{i\omega t}$$

and in general there may be additional terms to account for cross couplings between the various modes of motion.

Each of these force components and the cross coupling terms can be measured experimentally, or calculated from linear theory, for each degree of freedom over all ω and it is then possible to solve all the equations of motion simultaneously to give the full dynamic behaviour of the structure and in the process determine the forces acting on the body for structural analyses.

5.2.2. Application to wave power systems

The analysis can, in principle, be extended to wave power systems by incorporating additional terms in the equations of motion to account for the external damping and inertia of the conversion and transmission system, forces resulting from moorings and, by considering additional degrees of freedom, even the response of multiple structures, devices with several linked body elements, can be considered. The value of developing such an analytical tool is that it will be the only way of obtaining early estimates of the forces acting on the device, of the performance which can be expected from a moored floating device with realistic power take off systems and indicate what design changes would need to be made to improve its characteristics.

The Salter shape, for example, has been designed to give its best performance when the only motion is roll about the centre of the rear section and it is only intended to extract power from this motion. Seakeeping studies will be expected to show a tendency for heave and sway motions to be present which could have a serious effect on the device performance. Salter has proposed a design involving a very long string of ducks mounted on a rigid or semi-rigid spine which can make use of the limited crest length of waves in real seas to limit the unwanted motions through phase cancellations. Such a spine which is in any way rigid may prove so difficult to engineer that a different construction, say with a shorter spine and a rear balancing float - which may in turn require a modified duck shape - may have to be contemplated.

The Cockerell raft on the other hand has only ever been tested in a free floating mode and it is an essential feature of this design that each element is a stable component against which its neighbours react. Nevertheless, the full effect of realistic loading systems will have to be determined for this as for any other device.

The large Masuda system with multiple chambers apparently depends for its performance on stability in pitch and heave, although designs should exist where this is not necessary. Such stability could be provided by making the structure so large that response to wavelengths in the Atlantic spectrum is minimal or, by making use of the taut line mooring technique which has been developed for the North Sea oil platforms where the device would be held down against its own buoyancy.

5.3 Survival in Storm Conditions

One aspect of wave power common to all devices relates to the ability of each to cope with the very severe conditions which exist in the Atlantic. The scatter diagram indicates a .1% occurrence of waves with a significant wave height of around 14 m corresponding to peak waves of around 20 m in height and the predicted 50 year wave is 34 m high.

The air-water interface is the worst place to be in severe storm conditions and this has led to thoughts of arranging for devices to submerge to a safe depth in extreme conditions. However, the high cost of submarine technology would suggest that if possible the devices should be designed to ride out storms. Earlier in this Note it was observed that the scatter diagram showed that on only relatively few occasions did the apparent wave slope exceed 1:20. Although slopes of 1:10 will in fact be common in individual waves it is nevertheless clear that in general the extremely high seas will have a proportionately long wavelength and period and on the principle of the cork on the pond, devices could well be expected to ride such waves. Against this, very confused crossed seas can occur which could lead to erratic and damaging structural motions and there must be a probability that very steep waves and plunging breaking waves will occur. No statistics for the occurrence of plunging breakers have been found, but if they should occur the effect on devices could be catastrophic and this complete question therefore requires further careful study. Similar questions arise when considering the extreme loads which mooring systems will be required to withstand.

5.4 Reliability, Maintenance and Plant Life Considerations

In a situation where it is not at all clear what components are likely to be included in the selected 'best' system it is only possible to indicate the range of issues involved. It has been suggested that wave power devices should be designed and constructed as cheap expendable units which can easily be replaced or salvaged. At present it is not at all clear that it will be possible to consider units either to be 'cheap' or in any land based sense 'easily replaceable' except as complete installed units. On both counts therefore there would seem to be a strong incentive to design the device and machinery as a maintainable unit of the highest reliability and life.

The main structural elements, which, because they are not required to carry cargo, can have a much higher proportion of their displacement weight in structural material than is common in shipbuilding practice, should be capable of achieving a very long life. Surviving Mulberry Harbour units point to the potential longevity of reinforced concrete structures.

Exposed hinges, bearings or even gears, particularly those which are below the water line on the other hand, cannot be expected to have a long life unless expensive units which can be guaranteed 'sealed for life' can be produced. Otherwise the system must be designed so that the consequences of failure do not put either the main structure or the take off machinery at risk or alternatively that their replacement should be 'relatively' easy.

As for the conversion machinery itself, whilst it is possible to contemplate sealed units exposed to the elements, inboard mounting, in as close an approximation to an engine room environment as possible, would be much better. In this way it should be possible to provide access to the plant and machinery for routine servicing and maintenance during calm periods at least. This has an impact on the structural design.

There are many other issues to be considered under this heading including the effect on the security of the whole system, of the failure of one part either through storm damage or even collision, the need for workshops on board devices or the provision of support ships and the necessary harbourage and so on.

6. ENVIRONMENTAL IMPACTS

One of the major attractions commonly claimed for all of the renewable sources of energy is that they are non polluting. Except for possible spillages of oil from hydraulic or lubrication circuits this is certainly true. There are other environmental impacts which will have to be taken into account and a brief study carried out within the CEGB identified some of these and provided a qualitative assessment of their importance.

The visual impact of the device is only likely to be significant if it should be decided that devices must be located close in shore. All the more promising devices are intended for deep water operation, more than 10 km from the coast, and have such a low profile that even though they may be very large they will not be visible from land. The main visual impact will be due to the in shore terminal of the transmission link. Unless say hydrogen is the selected transmission medium and a chemical plant or some other industrial complex is established to process or use the hydrogen directly it is landed, this termination need have no greater impact than the large substations which already exist.

The construction and operation of wave power systems will create a need for large industrial complexes, dwellings and, possibly, new harbour facilities to be established and serviced by road and rail. Where no alternative exists but to develop green field sites then this would give rise to strong objections.

The main area where wave power might be expected to impact on the environment is in its modification to the sea. An effective wave power device is after all an ideal breakwater which could produce effects such as altering the sea bed by, for example, creating sand bars close to the device, reducing littoral drift and modifying coastal erosion and deposition patterns. The likely extent of these effects is not known but since the devices will tend not to extract much energy from storm waves,and short choppy seas are likely to be regenerated in the 10 to 20 km between the device and the shore, there would seem to be a very good prospect that these effects would not be particularly significant.

Similarly, ecological effects are not likely to give cause for concern and it may even be that the presence of large structures could attract new species of fish and plant life or encourage larger colonies of existing species. In fact, it is likely that the reverse effect of marine fouling on the performance and maintenance of devices will be much more severe.

The two areas where serious objection could be raised and which will therefore have to be studied very carefully, are the obstruction to navigation and the consequences of accidental damage both to ships and their crews and the devices resulting from collisions and of damage to coastal installations including harbours and even fixed platforms which could result from a device breaking free of its moorings.

7. COSTS AND PROSPECTS

It will be apparent from the preceding sections that many technical and engineering questions remain unanswered and that it is therefore far too early in the development of wave power for meaningful cost estimates to be made. Apart from the obvious questions of device design and efficiency and the selection of conversion and transmission components, there are a number of other factors to consider. These include the optimisation of the design output rating, which will depend not only on the detailed characteristics of the energy supply but also on the degree of randomness and the load factor which are acceptable on the electricity supply system, the choice and availability of materials and even the capability of producing devices at a sufficient rate. Constructing each 1000 MW installation may require the equivalent of 60 half million tonne supertankers to be built and fitted out. There are in addition unknown maintenance and operating costs which will probably include special support ships and harbourage.

The Report 'Energy Conservation' (1974) by the Central Policy Review Staff suggested that wave power might cost as little as £420 per kW. The CEGB preliminary study, (Denton, et al. 1975), by analogy with supertanker costs, suggested a likely cost band of £400 to £800 per kW. Further studies based on more recent device size and performance estimates, using ship-building costs as a guide, and including sums for fixed off shore control platforms and a purely notional conversion and transmission system, tend to confirm this cost band. One interesting effect which has been identified is that the system cost will be sensitive to the design output rating. Whereas the conversion and transmission equipment will tend to contribute a fixed cost, £ per kW, the structural elements, the devices, the moorings and the control platform will have costs determined more from seakeeping and survival considerations than the power rating. The contribution to the overall cost from these items will tend to reduce as the reciprocal of the output rating and there will apparently be a strong incentive to choose a large, say, more than 100 kW m^{-1}, design output rating.

The value of a given wave power installation in £ per kW on the other hand, will be strongly dependent on the load factor of the power it delivers and it has already been seen that this will fall rapidly as the design output power level is increased. If, for example, the 100 kW m^{-1} output level corresponds to wave powers of 200 kW m^{-1} and above (after taking device and conversion efficiencies into account) the load factor from Figure 6 would be about 50% in winter and only 30% taking the year as a whole. Alternatively, designing for an output rating of 50 kW m^{-1} could increase these to 66% and almost 50% respectively. Over the year the energy saved by each could amount to 260 MWh m^{-1} and 220 MWh m^{-1} respectively. The value of the energy saved is not therefore greatly affected by the design rating but in £ per kW terms appears to go as 1/design rating, so costs and values tend to move together and it is not clear where the optimum will lie. The numerical value of the fuel cost saving is equally difficult to predict depending as it does on future fossil fuel price levels but it can be shown that if these rise in real terms the capitalised value of those savings could be comparable with the estimated costs.

It has been demonstrated that ocean waves are an abundant source of power, possibly the largest exploitable naturally recurring source available to the United Kingdom. Several potentially efficient device types have been identified which need be no larger than is commonplace in shipbuilding. Having taken account of the likely characteristics of these devices and their associated power conversion equipment, it has been shown that the extreme variability of the energy source can be reduced to more manageable proportions. Output power densities, on the other hand, remain at a sufficiently high level that 'power station sized' assemblies of about 1000 MW may need to be no more than 10 to 20 km long. Although wave power cannot be regarded as firm power there is a seasonal variation in the supply which corresponds to the variation in demand on the CEGB system. There is, in addition, the possibility that the scale of the weather, and therefore wave, system is sufficiently small in relation to the United Kingdom, that the combined output from widely spaced installations could be more consistent than the output from each independently.

Taken overall, it would appear that if satisfactory solutions can be found to the many formidable technical and engineering problems without incurring an undue increase in costs, there is a possibility that wave power could make a valuable contribution to Britain's energy needs. Finally, it must be emphasised that this view is based on still limited theoretical studies and model tests at a small scale and it will take several years of intensive study to confirm the prospects for wave power and many more to develop it on a commercial scale.

8. ACKNOWLEDGEMENTS

The information in this Note is based on studies undertaken by the CEGB Research Department at their Marchwood Engineering Laboratories and is published with the permission of the Central Electricity Generating Board.

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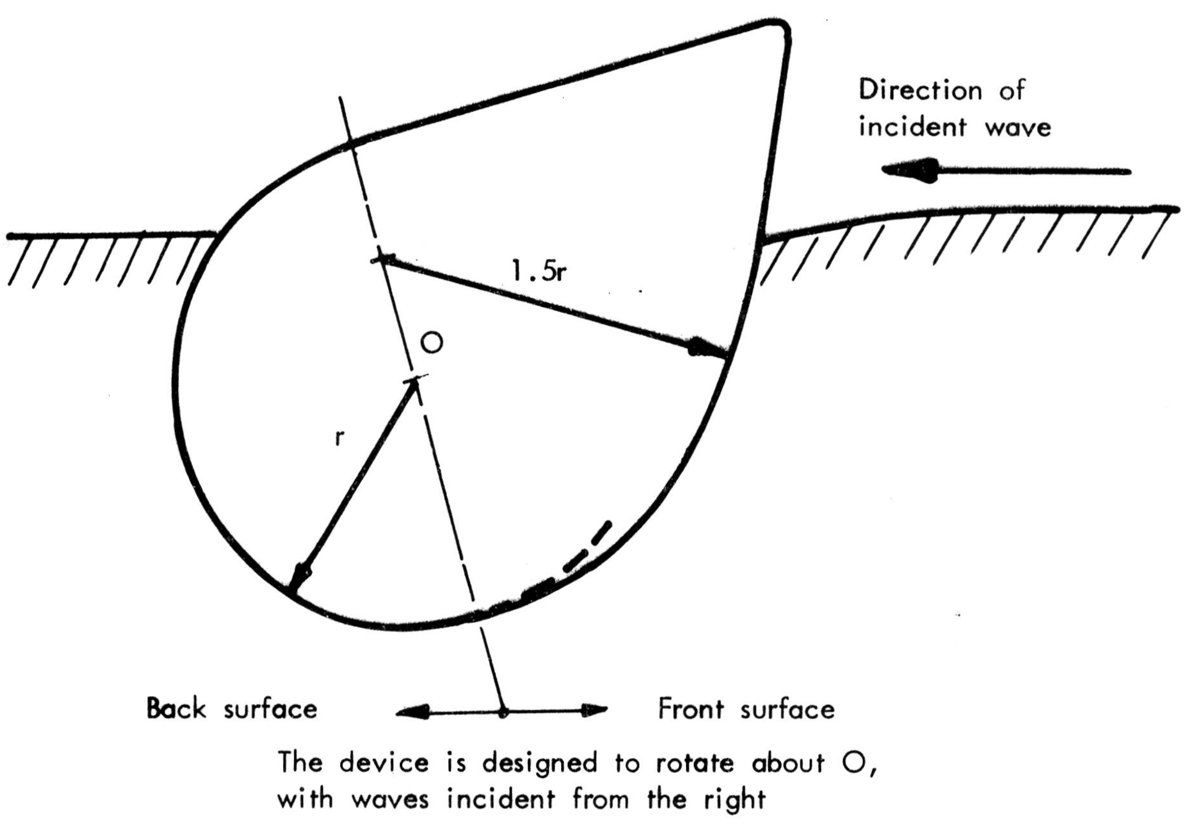


FIGURE 1. THE GEOMETRY OF THE SALTER CAM

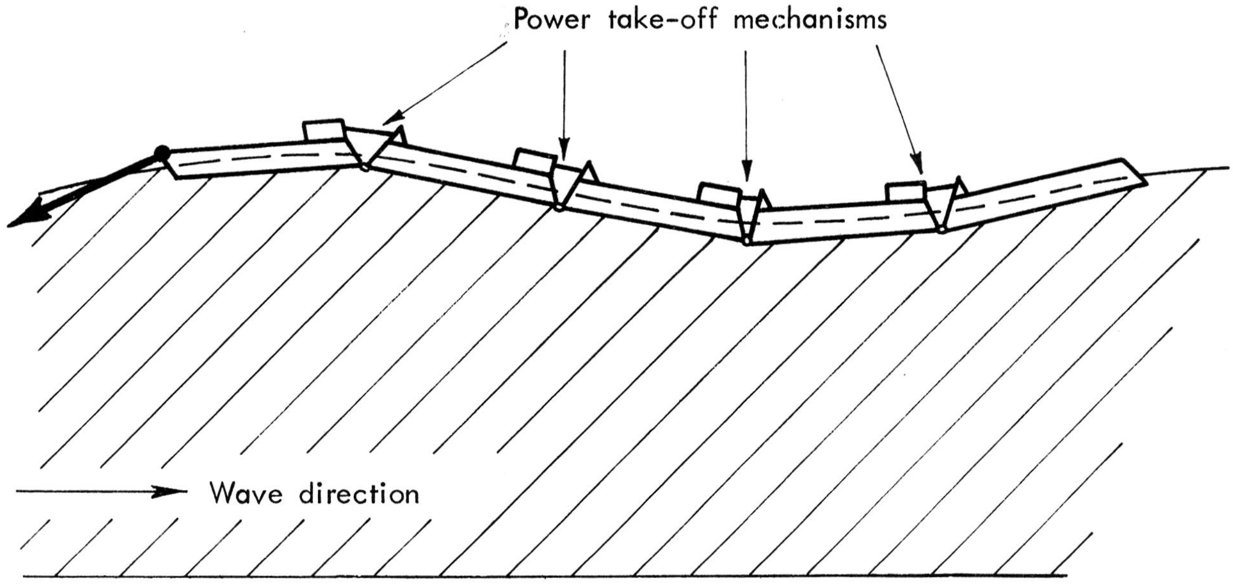


FIGURE 2. THE COCKERELL WAVE CONTOURING RAFT

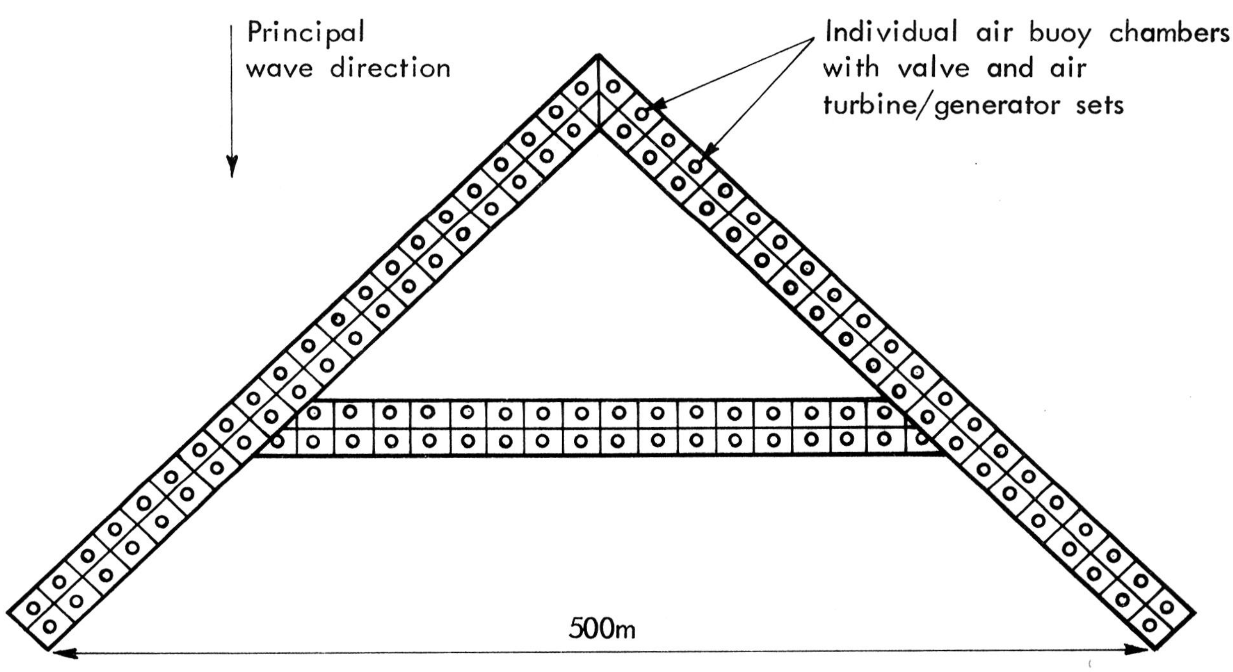


FIGURE 3. PLAN VIEW OF A MULTI CHAMBER MASUDA BUOY

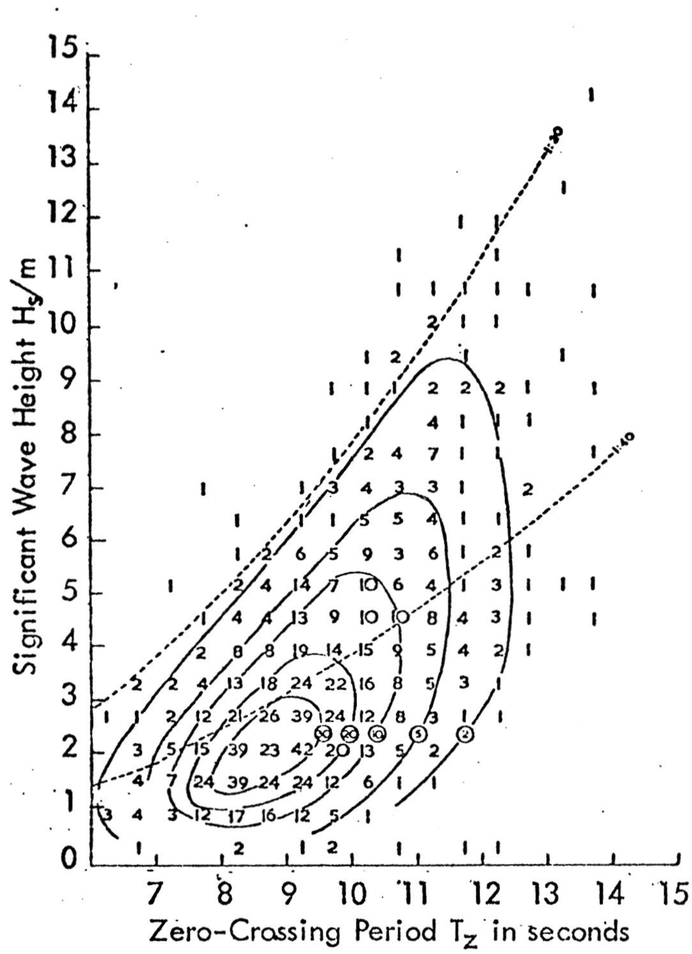


FIGURE 4. SCATTER DIAGRAM RELATING SIGNIFICANT WAVE HEIGHT TO ZERO CROSSING PERIOD FOR THE WHOLE YEAR AT OWS STATION INDIA SHOWING THE FREQUENCY/1000 OF H_s, T_z COMBINATIONS AND LINES OF CONSTANT WAVE SLOPES (1:20, 1:40)
(AFTER DRAPER 1967)

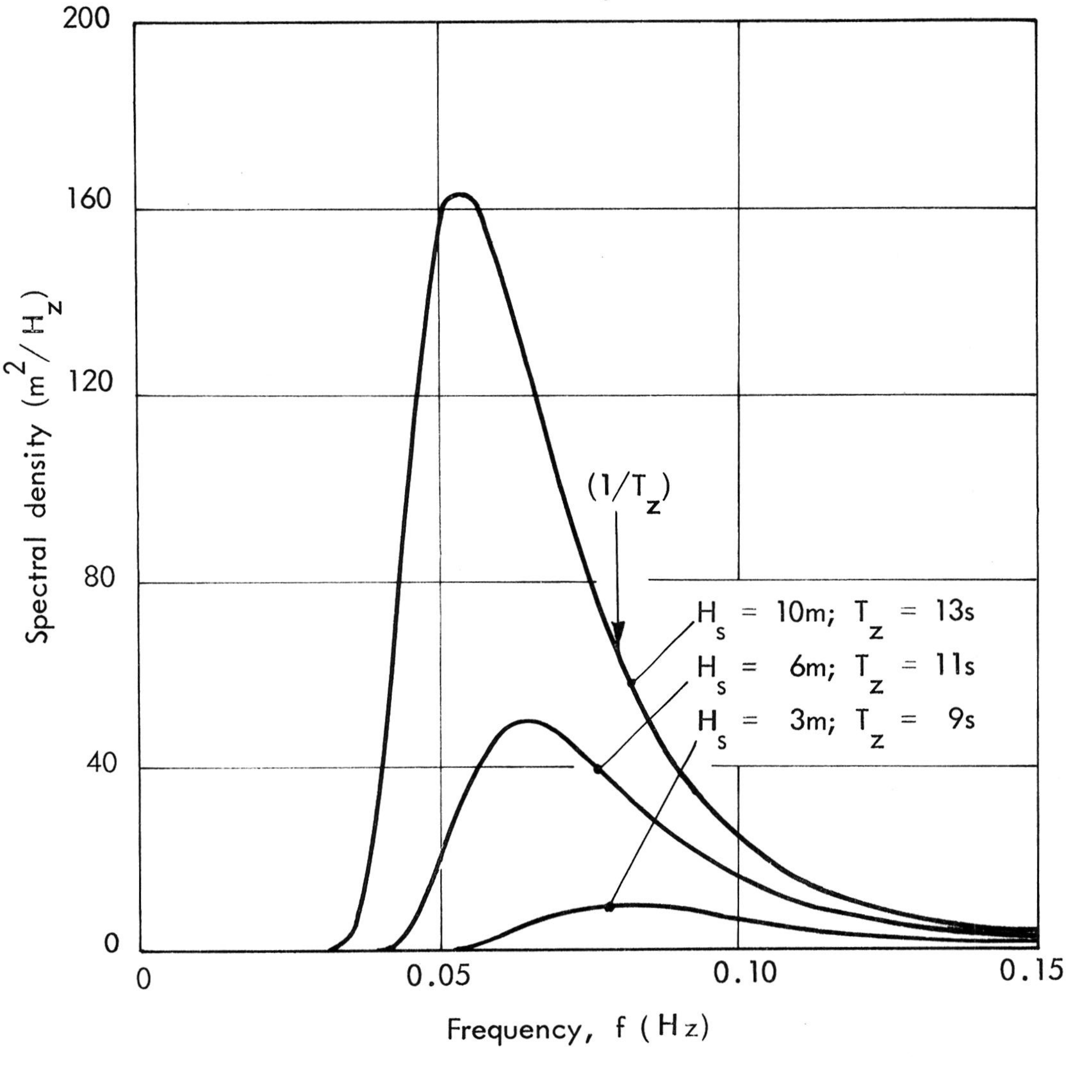


FIGURE 5. TYPICAL PIERSON-MOSKOWITZ SPECTRA

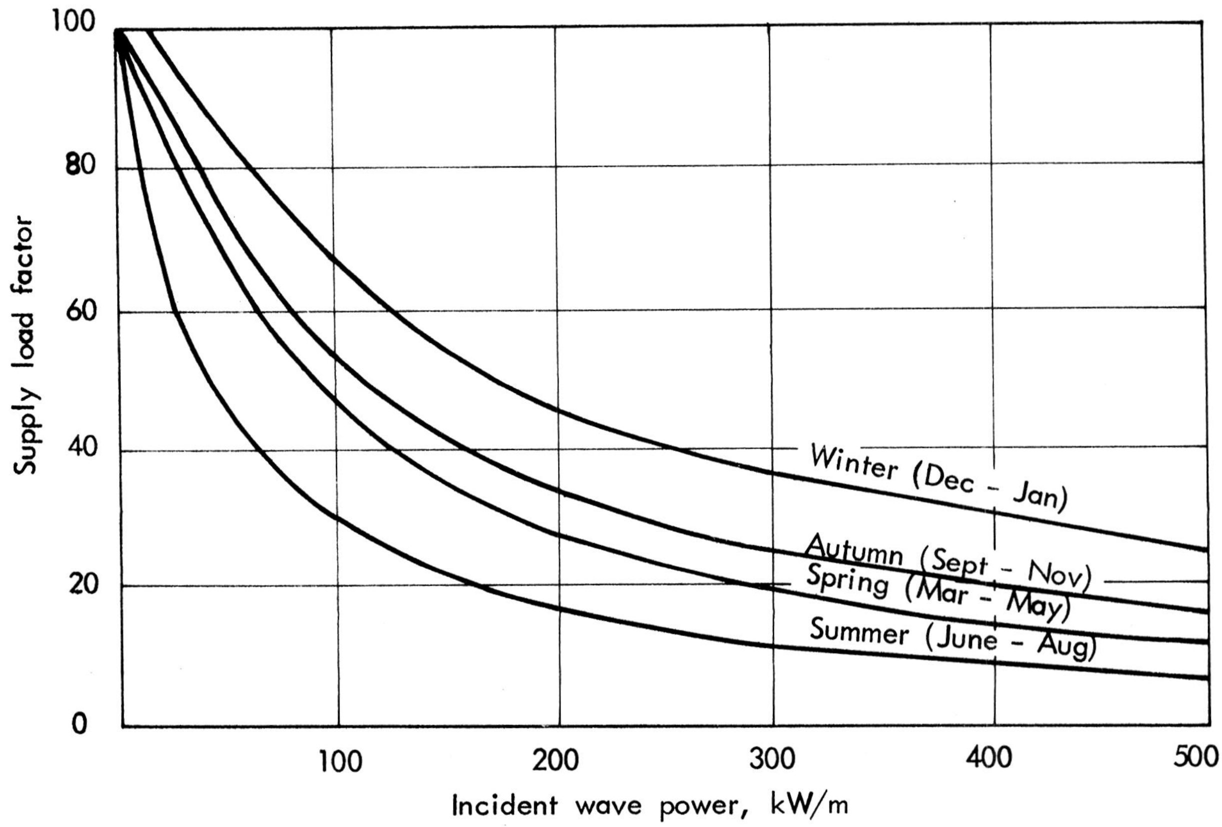


FIGURE 6. SUPPLY LOAD FACTOR CURVES FOR STATION INDIA (1955 - 1965)

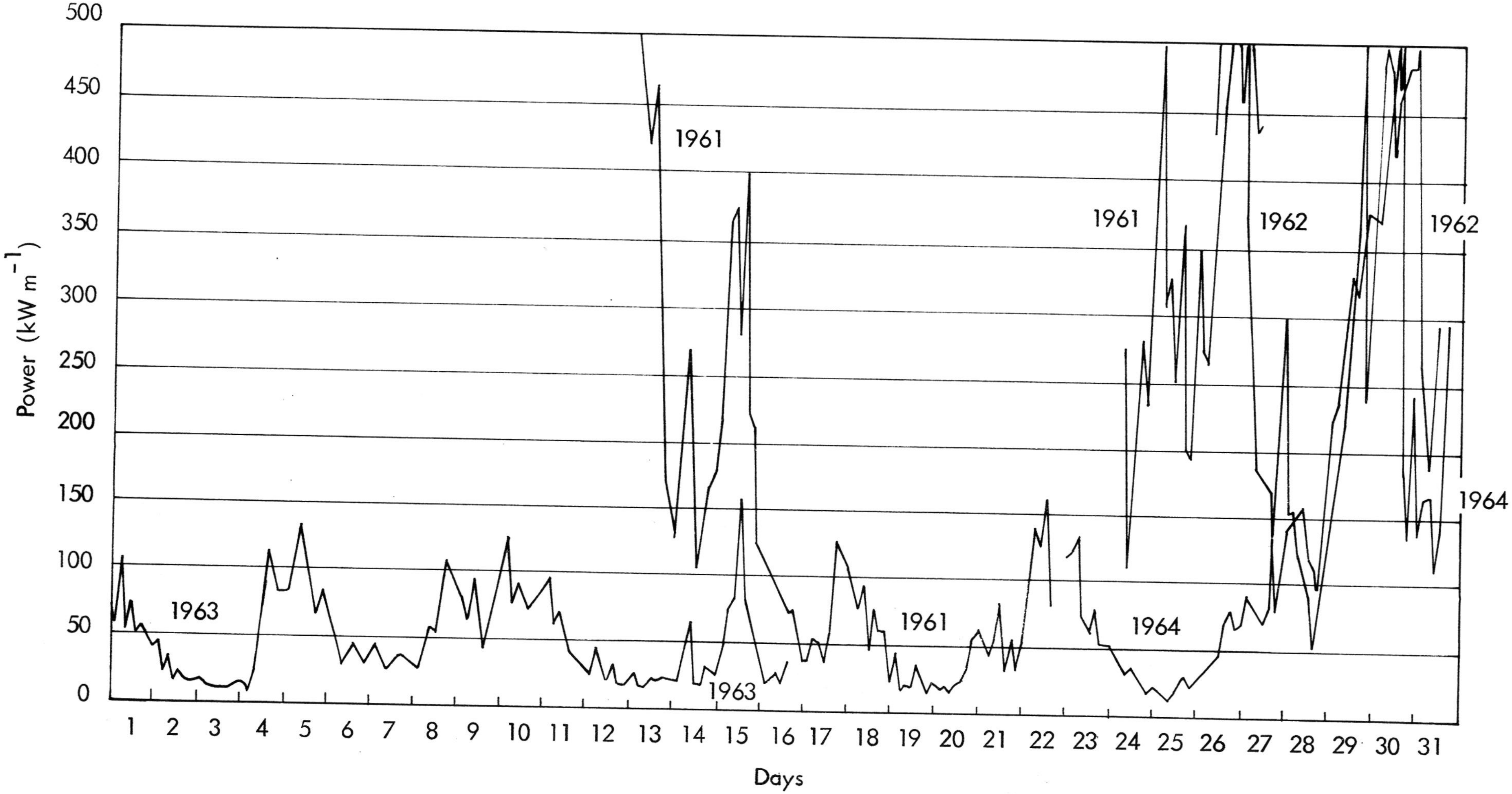
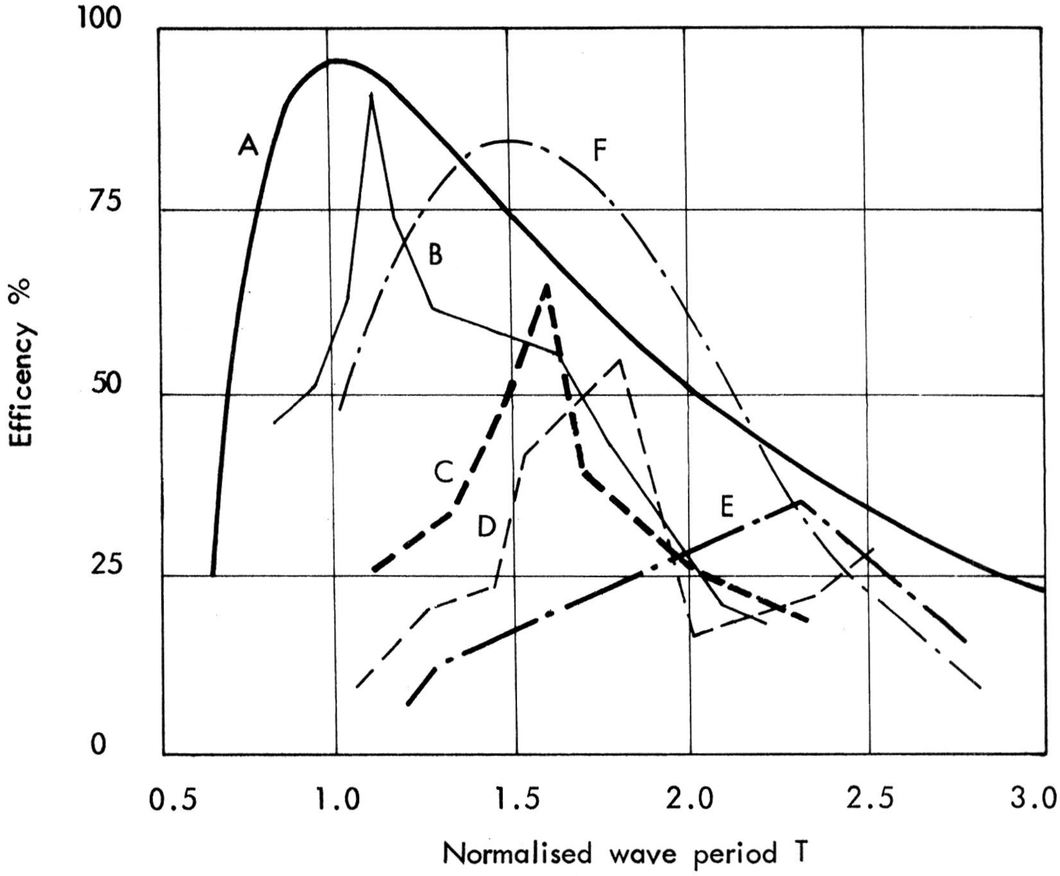


FIGURE 7. WAVE POWER AT INDIA - 'JANUARY'



——— (thick solid)	Theory (CEGB)
——— (thin solid)	10cm Duck (Oct. 1974)
– – – – (thick dashed)	50cm Duck I/I_o = 0.92
– – – – (thin dashed)	50cm Duck I/I_o = 1.42
—— - —— (thick dash-dot)	50cm Duck I/I_o = 1.92
—— - —— (thin dash-dot)	10cm Duck - Salter Sept 1975, deeply immersed

10cm test at Edinburgh University

50cm tests at Hythe, Southampton, May 1975

FIGURE 8. PERFORMANCE OF THE SALTER DUCK

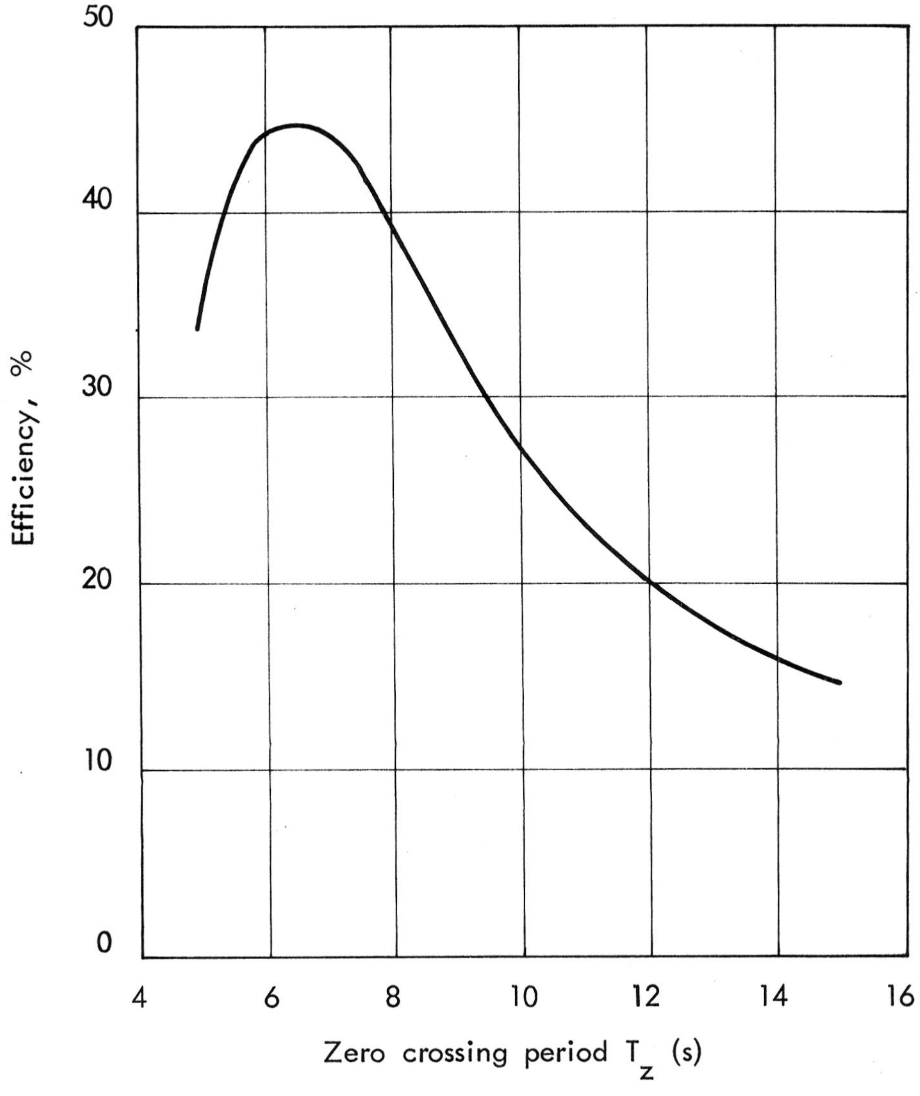


FIGURE 9. NOTIONAL SEA PERFORMANCE OF A SALTER DUCK (18m DIAMETER)
(BASED ON CEGB TESTS, MAY 1975, FIG. 8 CURVE C)

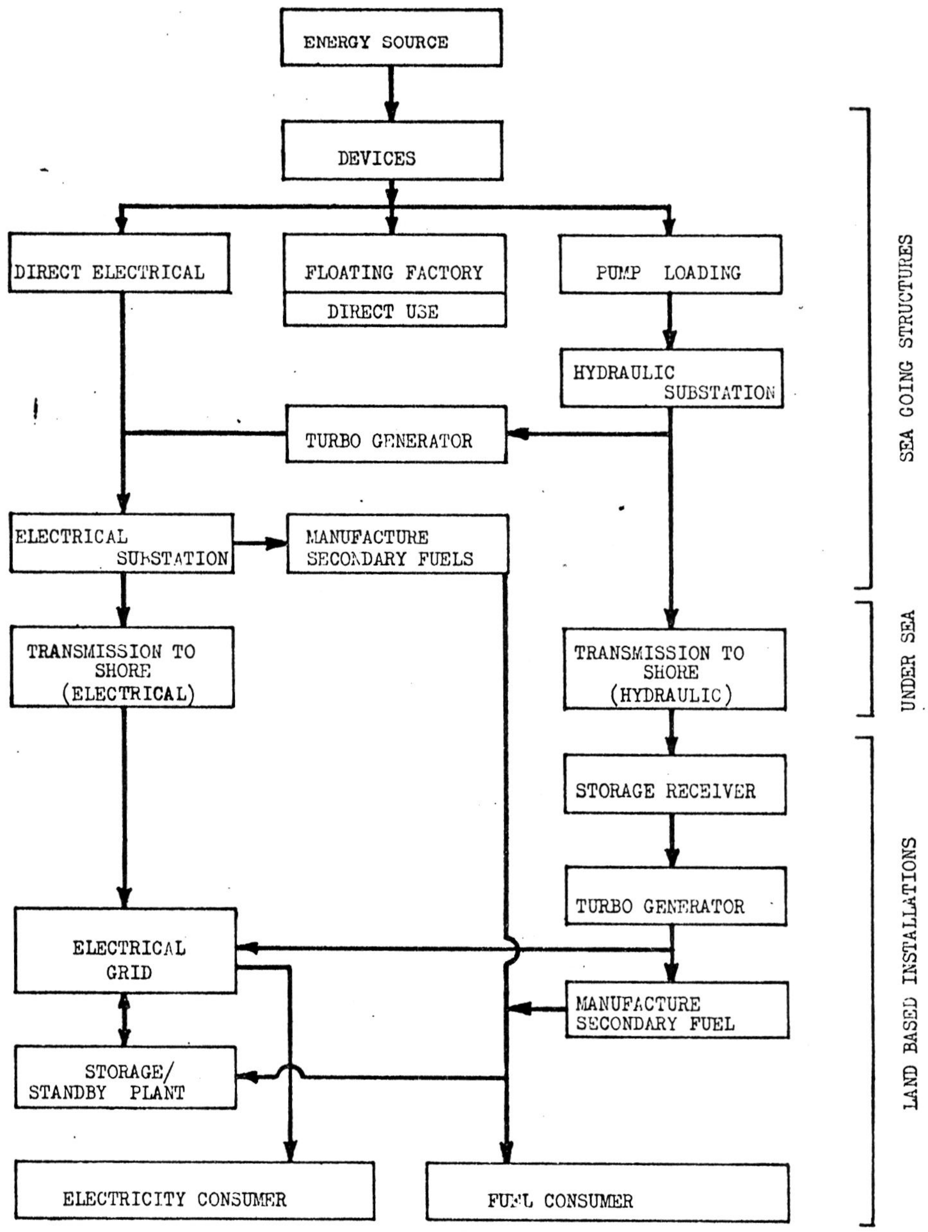


FIGURE 10. POSSIBLE WAVE POWER SYSTEMS

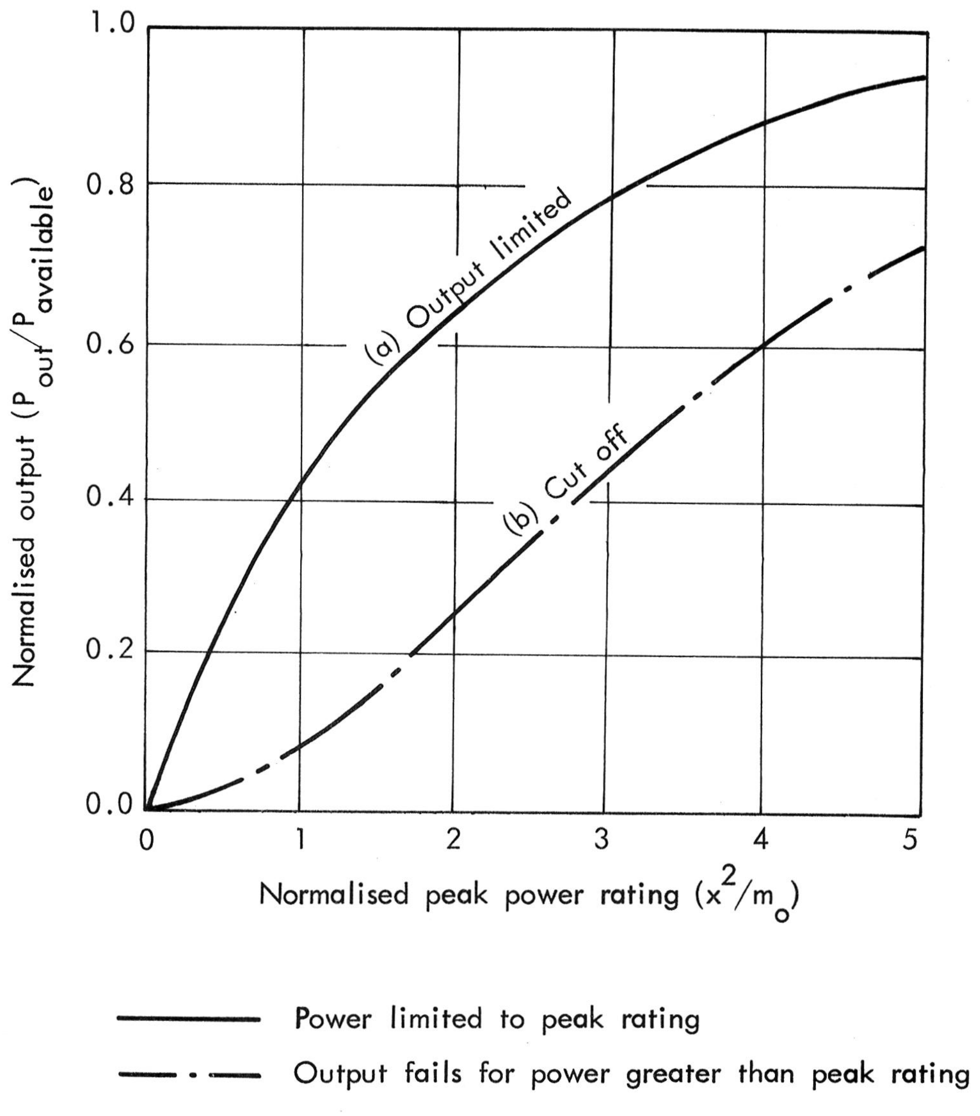


FIGURE 11. POTENTIAL OUTPUT AS A FUNCTION OF THE RATIO OF PEAK/MEAN POWER ON CONVERSION PLANT (ASSUMES RAYLEIGH DISTRIBUTION OF WAVE HEIGHT)

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